arXiv:astro-ph/0311168v1 7 Nov 2003

ENERGY AND ANGULAR MOMENTUM DEPOSITION DURING COMMON ENVELOPE EVOLUTION

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ABSTRACT

I consider three processes which enhance mass loss rate from a common envelope of a giant star with a main sequence or a white dwarf companion spiraling-in inside its envelope. I consider deposition of orbital energy and orbital angular momentum to the giant's envelope, and in more detail the formation of jets by an accreting companion and their propagation in the envelope. I find that in many cases the deposition of orbital angular momentum to the envelope may be more important to the mass loss process than the deposition of orbital energy. Jets blown by an accreting companion, in particular a white dwarf, orbiting inside the outer regions of the giant's envelope may also dominate over orbital energy deposition at early stage of the common envelope evolution. These imply that studies which ignore the deposition of angular momentum to the envelope and the effects of the accreting companion may reach wrong conclusions.

Subject headings: stars: binaries − stars: evolution − stars: AGB and post-AGB − stars: mass loss − jets

1. INTRODUCTION

As a star in a binary system swells to become a giant it engulfs its companion if the orbital separation is smaller than some critical value and if the companion is not too massive; a common envelope (CE) phase commences. (for a review see Iben & Livio 1993, and Taam & Sandquist 2000). Because of tidal interaction and friction, the orbit shrinks. Several parameters can be defined to characterized the CE evolution (e.g. Livio & Soker 1988), but the most commonly used parameter is the ratio of the binding energy of the ejected envelope $\Delta E_{\rm bind}$ to the orbital energy that is released during the CE phase $\Delta E_{\rm orb}$: $\alpha_{\rm CE} \equiv \Delta E_{\rm bind}/\Delta E_{\rm orb}$. Note that different definitions for the binding energy exist (e.g., O'Brien, Bond, & Sion 2001). Since the orbital energy that is released depends mostly on the final orbital separation, the value of $\alpha_{\rm CE}$ can be in principle calculated for systems whose final orbital separation is known, assuming the giant structure at the

onset of the CE is known (O'Brien et al. 2001; Maxted et al. 2002). The use of the $\alpha_{\rm CE}$ is common also in numerical simulations of the CE phase (e.g. Sandquist, Taam & Burkert 2000 for a recent paper). However, numerical simulations can't include the effect of enhanced mass loss rate from giant stars that have a very high mass loss rate. The spun-up envelope of red giant branch (RGB) and asymptotic giant branch (AGB) stars may have a much higher mass loss rate, with the energy source being the giant's luminosity rather than the orbital energy (Soker & Harpaz 2003).

In some systems the usage of the above expression in a simple manner yields $\alpha_{\rm CE} > 1$. For example, Maxted et al. (2002) assume that negligible mass has been lost prior to the onset of the CE phase in PG1115+166, and find $\alpha_{\rm CE} > 1$. This led some researchers to argue that the energy stored in the envelope, and in particular the ionization energy, i.e., the energy released when the envelope material recombines, is the extra energy needed to expel the CE (e.g., Han, Podsiadlowski, & Eggleton 1994; Dewi & Tauris 2000; Maxted et al. 2002). This proposed mechanism was criticized in previous papers (Harpaz 1998; Soker 2002; Soker & Harpaz 2003). In Soker (2002) I criticized the paper by Maxted et al. (2002) for not considering the mass lost from the envelope prior to the onset of the CE, when the system is synchronized, i.e., the giant's rotation period equals the binary orbital period, and the binary orbital shrinkage proceeds very slowly. Eggleton (2002), for example, notes that a close companion may substantially enhance mass loss rate prior to the onset of a Roch lobe overflow (RLOF), with the possibility of preventing a CE phase altogether.

Soker & Harpaz (2003) criticize Han et al. (2002) for claiming that the ionization energy in the envelope is a significant factor in the CE evolution. Soker & Harpaz (2003) consider the mass lost by RGB stars as they expand by a relatively large factor from the moment of synchronization to the RLOF. Soker & Harpaz then argue that Han et al. (2002) include a mass loss rate prior to the onset of the CE that is too low, and do not include the energy radiated by the accreting white dwarf companion, as well as that emitted by the core of the giant star. In a later paper Han et al. (2003) briefly refer to Soker & Harpaz criticism, keeping the dispute alive. Since the applicability of the $\alpha_{\rm CE}$ parameter is a fundamental question in the CE process, and the CE evolution is the channel for the formation of many close binary systems, I elaborate on some questions regarding energy and angular momentum budget in the CE phase. In the first several sections I study the way by which an accreting companion can deposits energy via jet formation. I then (section 7) put all into a coherence picture. A short summary is in section 8.

2. MASS ACCRETION RATE

The Bondi Hoyle mass accretion rate inside the envelope is (Armitage & Livio 2000)

$$\dot M_{\rm acc} = \pi \left(\frac{2GM_2}{v_r^2 + C_s^2} \right)^2 \rho_e (v_r^2 + C_s^2)^{1/2}, \qquad (1)$$

where M_2 is the mass of the accreting companion, v_r is the relative velocity of the accreting companion relative to the unperturbed envelope, ρ_e is the unperturbed envelope density at the

location of the accreting star, and C_s is the sound speed inside the unperturbed envelope. The companion orbits the giant's core at the Keplerian velocity v_K. However, the relative velocity v_r will be somewhat smaller because the envelope is likely to be spun-up by the spiraling-in companion. Considering also that the motion inside the envelope is mildly supersonic (Armitage & Livio 2000), I use the approximation $(v_r^2 + C_s^2)^{1/2} \simeq v_K$. The difference in the value of the accretion rate as a result of this approximation will be absorbed in the parameter ζ. For an AGB envelop density a good approximation for the present purpose is (Soker 1992)

$$\rho_e = \frac{M_{\rm env}}{4\pi R_*}\frac{1}{r^2}, \tag{2}$$

where $M_{\rm env}$ is the envelope mass and R_* the stellar radius. For the formation of a CE the companion shouldn't bring the envelope to corotation, hence $M_2 \lesssim 0.3M_1$. As it spirals-in, the mass inward to the secondary orbit, $M_1(a)$ decreases, and the mass ratio can become as large as $M_2/M_1(a) > 1$. Here $M_1(a) = M_c + M_{\rm env}a/R_*$ is the giant mass inward to the companion location, a is the distance of the companion from the core, and M_c is the giant's core mass. However, to draw my main conclusions I am interested in the accretion process in the outer regions of the envelope, where a crude but adequate approximation can be $M_1(a) \gg M_2$. The Keplerian velocity is then simply $v_K = [GM_1(a)/a]^{1/2}$. By using this and equation (2) in equation (1), I derive the accretion rate in the form

$$\dot M_{\rm acc} \simeq 2\pi\zeta\frac{M_{\rm env}}{\tau_K}\left[\frac{M_2}{M_1(a)}\right]^2\frac{a}{R_*}, \tag{3}$$

where $\tau_k = 2\pi a/v_K(a)$ is the Keplerian orbital period. For a WD with $M_2 \sim 0.6M_\odot$, inside an AGB stellar envelope with $M_{\rm env} \simeq 1M_\odot$, $M_c \simeq 0.6M_\odot$, $R_* \simeq 1-2$ AU, I find $\dot M_{\rm acc} \sim \zeta M_\odot~{\rm yr}^{-1}$ in most of the envelope. This is a too high an accretion rate as it exceeds the Eddington limit of

$$\dot M_{\rm Edd} = 4\pi m_p c R_2 \sigma_T^{-1} = 10^{-3}\frac{R_2}{R_\odot}M_\odot~{\rm yr}^{-1}, \tag{4}$$

where R_2 is the radius of the accreting star, m_p the proton mass, c the speed of light, and σ_T the Thomson cross section. I find that $\zeta \sim 10^{-3}$ and 10^{-5}, for main sequence stars and WDs, respectively. As the accreting star swells, the accretion rate increases, possibly leading for further expansion of the secondary's envelope.

3. ANGULAR MOMENTUM ACCRETION RATE

I turn now to consider the specific angular momentum of the accreted mass. For a density gradient perpendicular to the relative velocity of the ambient medium and the accreting mass (the y direction) of $\rho = \rho_0(1 + y/H)$, the specific angular momentum of the accreted mater is

$$j_{\rm acc} = \frac{\eta}{4H}\frac{(2GM_2)^2}{v_r^3}, \tag{5}$$

where $\eta \sim 0.25$ is the ratio of the accreted angular momentum to that entering the Bondi-Hoyle accretion cylinder, and it depends on the Mach number and the equation of state (Livio et al. 1986). For the envelope density profile given in equation (2) $H = r/2$, but at early AGB phases, before much of the envelope has been lost and the star did not reach its full size on the AGB, it is steeper with $H \simeq r/4$; I take $H = r/2$, as it is not a bad approximation, and it also fits a wind outside the envelope. Taking again the Keplerian velocity for the relative velocity, I find

$$j_{\rm acc} \simeq 2\eta \left[\frac{M_2}{M_1(a)} \right]^2 [GM_1(a)a]^{1/2}. \tag{6}$$

If $\zeta \ll 1$ and the mass is accreted with an impact parameter smaller than the Bondi-Hoyle radius, then $\eta \ll 0.25$. On the other hand, if a polar outflow is formed such that it prevents some accretion from the polar directions, i.e., most of the accreted mass comes from and near the equatorial plane, then the specific accreted angular momentum will be higher. To form an accretion disk, $j_{\rm acc}$ should be larger than the angular momentum of a Keplerian motion on the companion's equator $j_2 = (GM_2R_2)^{1/2}$, where R_2 is the radius of the accreting companion. The condition $j_{\rm acc} > j_2$ gives

$$2\eta \left[\frac{M_2}{M_1(a)} \right]^{3/2} \left(\frac{a}{R_2} \right)^{1/2} \gtrsim 1. \tag{7}$$

For the formation of a CE, $M_2/M_1 \lesssim 0.3$, otherwise the companion brings the envelope to corotation. Inside the envelope, where $M_1(a) < M_1$, this ratio becomes larger. Condition (7) then reads $a \gtrsim 100R_2$.

4. A MAIN SEQUENCE COMPANION

From equation (7) it can be seen that an accretion disk will not form around a main sequence companion in a CE phase well inside the envelope, while in the outer regions of the envelope an accretion disk can be marginally formed. When the companion enters the envelope, the density profile is very steep, and for a short time the accretion rate of specific angular momentum is very high; at this stage a temporary accretion disk might be formed, if was not present before i.e., due to Roche lobe over flow (RLOF) or accretion from a wind. In any case, the mass accretion rate increases substantially as the companion enters the envelope; a short burst of two opposite jets may result from this phase.

Outside the envelop the wind's density also falls as r^{-2} (for a wind with constant speed and mass loss rate), and we can crudely use equation (7). For a main sequence companion outside the envelope, M_2 is larger and/or the separation must be such that no tidal interaction occurs, i.e., $R \gtrsim 5R_*$, where R_*, as before, is the radius of the giant. These requirements make the formation of an accretion disk in detached systems much more likely (if the orbital separation is not too large).

The simple treatment above leads to a strong conclusion. While a main sequence star outside an AGB star (or other giants) may accrete and form an accretion disk (see Soker 2001 for the

conditions for that to occur), a main sequence star inside the giant envelope will form an accretion disk for a short time. It is not clear if jets can be blown during this short time. If jets, or collimated fast wind (CFW), are blown outside the envelope a bipolar PN is formed. The results may explain the observations that most PNe with close binary nuclei are not bipolar PNs. The exception in NGC 2346, which has the largest known orbital period (Bond & Livio 1990; Bond 2000). In that system the onset of the CE probably occurred at a late stage, and the companion blew the CFW while still outside the envelope (Soker 2002).

We saw above that an accretion disk is unlikely to be formed around a main sequence companion spiraling-in inside the envelope. However, the accreted angular momentum spins-up the companion, enhancing the magnetic activity of an accreting main sequence companion with a convective envelope. Enhanced magnetic activity of spun-up main sequence companions which accrete from the winds of AGB stars was considered before, for main sequence companions of WDs (Jeffries & Stevens 1996), and for companions of central stars of PNs (Soker & Kastner 20002). Here I consider the case of accretion inside the envelope rather than from a wind.

During the short time of the CE phase and the following PN phase, most of the accreted angular momentum will be distributed in the outer convective layer of the accreting main sequence companion. Let the mass in this layer be $M_{\rm con}$, and its moment of inertia $\delta M_{\rm con} R_2^2$. Equating the angular momentum in that layer to the accreted one gives an expression for the rotation period of the spinning main sequence companion (or at least its convective layer) $P_{\rm rot}$. The accreted angular momentum is $j_{\rm acc} M_{\rm acc}$, where $j_{\rm acc}$ is the specific accreted angular momentum as given by equation (6), and $M_{\rm acc}$ is the accreted mass, of order $0.01 - 0.05 M_\odot$ (Hjellming & Taam 1991). Neglecting the envelope angular momentum prior to accretion, gives

$$\delta M_{\rm con} R_2^2 \frac{2\pi}{P_{\rm rot}} \simeq 2\eta M_{\rm acc} \left[\frac{M_2}{M_1(a)}\right]^2 [G M_1(a) a]^{1/2}. \tag{8}$$

To an order of magnitude, I take for the average value during accretion $a \sim 50 R_\odot$, and $M_1(a) = 1 M_\odot$, and obtained the following scaled expression for the rotation period

$$P_{\rm rot} \simeq 5 \left(\frac{\delta M_{\rm con}}{5 M_{\rm acc}}\right) \left(\frac{\eta}{0.2}\right)^{-1} \left(\frac{R_2}{R_\odot}\right)^2 \left(\frac{M_2}{M_\odot}\right)^{-2} {\rm hrs}. \tag{9}$$

Since some angular momentum will be transferred to the inner radiative envelope, the rotation period will be somewhat longer.

A low mass main sequence companion is likely to end close to the core, hence being strongly influenced by tidal forces, as are main sequence companions in cataclysmic variables. Main sequence companions to WDs in cataclysmic variables are known to be magnetically active (Saar & Brandenburg 1999, and references therein); Saar & Brandenburg term them magnetically superactive stars, and review their properties in relation to other active stars. The typical rotation period is ~ 2 hours-2 days, and the magnetic activity cycle period of these stars is $5 - 50$ yr (this is the activity cycle, i.e., for the Sun it is 10 years, rather than the full 20 years cycle). In a previous

paper (Soker & Livio 1994) I proposed that a main sequence star emerging from a CE with an AGB star may, under certain conditions, transfers mass to the core (of the previous AGB star) at a rate of $\sim 10^{-6} - 5 \times 10^{-5} M_\odot$ yr^{-1}. If a disk is formed around the core, I proposed, then two jets may be blown, with a mass loss rate into the jets of $\sim 10^{-8} - 10^{-6} M_\odot$ yr^{-1}. If the magnetic activity cycle regulate the mass loss rate from the main sequence star to the core, then the jets will have a periodic (or semiperiodic) density variation.

5. A WHITE DWARF COMPANION

The situation with a WD companion is more complicated. Hachisu, Kato & Nomoto (1999) examine a spherically symmetric accreting WD. They find, for their prescribed mass loss rate, that a WD accreting at a rate of (the Eddington luminosity of a WD) $\dot{M}_{\rm acc} \gtrsim 10^{-5} M_\odot$ yr^{-1}, swells substantially, up to several solar radii. As its radius increases, the Eddington mass accretion rate increases, and the WD can swell to tens of solar radii, itself becoming a giant. However, the angular momentum of the accreted mass must be considered. Unlike an accreting main sequence star, the envelope formed around the WD is made completely of the accreted gas, hence has a large specific angular momentum. Let the radius of the swelled WD be R_s, the envelope mass $M_{\rm acc}$, and its moment of inertia be $I_s = k_s M_{\rm acc} R_s^2$, where $k_s \sim 0.2$. Using equation (6) for the specific angular momentum of the accreted matter, assuming that no angular momentum is lost, and assuming that the WD envelope rotates as a solid body, I derive the ratio of the WD envelope angular velocity to the break-up velocity on its equator, i.e., the Keplerian angular velocity on the equator $\omega_{\rm Kep}$,

$$\frac{\omega_s}{\omega_{\rm Kep}} = 0.8 \frac{\eta}{k_s} \left(\frac{R_s}{10 R_\odot} \right)^{-1/2} \left(\frac{a}{100 R_\odot} \right)^{1/2} \left[\frac{M_2}{0.25 M_1(a)} \right]^{3/2} . \tag{10}$$

Some angular momentum will be lost, however, via mass loss, as is the case in accretion disks. This show that, under these assumption, the WD will form a fast rotating envelope, which is highly deformed to an oblate shape, possibly with 'dips' along the poles, i.e., something similar to a thick accretion disk. Such an envelope may form collimated fast wind (CFW) along the polar directions.

A full two-dimensional numerical calculation is required to find the fate of a WD accreting mass with high specific angular momentum. Here I only point to the possibility that the accreting WD may blow jets. The accreting WD has a strong energy source, the nuclear-burning on its surface, which is $L_{WD} \simeq 2 \times 10^4 L_\odot$ for a WD of mass $0.6 - 0.8 M_\odot$. Typical for accretion disks is that $\sim 10\%$ of the accreted mass is blown in jets. If 10% of the nuclear-burning energy goes to blow jets, I can estimate the mass loss rate to the two jets, $\dot{M}_j$, from $0.1 L_{\rm WD} = \dot{M}_f v_e^2/2$, where v_e is the escape velocity from the poles of the swollen WD. This gives,

$$\dot{M}_j \simeq 10^{-4} \left(\frac{R_s}{1 R_\odot} \right) M_\odot \ {\rm yr}^{-1}, \tag{11}$$

which holds if the accretion rate is $\dot{M}_{\rm acc} \gtrsim 10^{-3} M_\odot$ yr^{-1}.

6. JET PROPAGATION

I now consider the possibility that two not-well collimated jets (i.e., a CFW), one at each side of the equatorial plane, are blown by an accreting WD (or a neutron star) companion. Jets blown by the core of an AGB star, via the destruction of a brown dwarf for example, can easily clean a path inside the envelope and emerge on the poles (Soker 1996). When the orbiting companion blows the jets, the jets need to penetrate different regions along the orbit, hence they are less likely to emerge on the surface. The relevant properties of the highly supersonic jet are its speed v_j, its half opening angle (from its symmetry axis to its edge) $\theta \ll 1$, and the mass loss rate into each jet $\dot{M}_j = \beta \dot{M}_{\rm acc}$, where β is the fraction of the accreted mass blown into each jet. The density inside the jet, which propagates perpendicular to the orbital plane along the z axis, is

$$\rho_j = \frac{\beta \dot{M}_{\rm acc}}{\pi z^2 \theta^2 v_j}. \tag{12}$$

The envelope density, by equation (2), is

$$\rho_e = \frac{M_{\rm env}}{4\pi R_*} \frac{1}{a^2+z^2}, \tag{13}$$

where a is the orbital separation. The head of the jet proceeds at a speed v_h given by the balance of pressures on its two sides. Assuming supersonic motion, this equality reads $\rho_e v_h^2 = \rho_j (v_j - v_h)^2$. Eliminating v_j/v_h, using equation (13) for ρ_e, and equation (12) for ρ_j, with $\dot{M}_{\rm acc}$ from equation (3), I derive the following expression

$$\frac{v_j}{v_h} - 1 \simeq \frac{z}{(a^2+z^2)^{1/2}} \frac{\theta}{2(\zeta\beta)^{1/2}} \left(\frac{v_j}{v_K}\right)^{1/2} \frac{M_1(a)}{M_2}. \tag{14}$$

Close to the jet's source, i.e., $z \ll a$, the jet's head proceed at a speed close to v_j. Further away it slows down, and because the jet is not well collimated, as was deduced in previous sections, i.e., $\theta \gtrsim 0.2$, we have $v_h \ll v_j$. Neglecting therefore the term '-1' in the last equation, I find for $z \gtrsim a$

$$\frac{v_h}{v_K} \lesssim \frac{(a^2+z^2)^{1/2}}{z} \frac{2(\zeta\beta)^{1/2}}{\theta} \left(\frac{v_j}{v_K}\right)^{1/2} \frac{M_2}{M_1(a)}. \tag{15}$$

As an example I take the following values: A jet from a WD with $v_j = 3000$ km s^{-1}, Keplerian velocity on the giant stellar surface of $v_K(R_*) = 30$ km s^{-1}, $\theta = 0.2$, $\zeta = 10^{-5}$, and a high efficiency of jet formation at the Eddington limit $\beta = 0.5$ (the mass which is blown in the jets is equal to the accreted mass), and $M_2 \simeq 0.2 M_1(R_*)$. At $z \simeq a$, and at $a \simeq 0.5 R_*$, equation (15) gives $v_h \lesssim 0.1(\theta/0.2)^{-1} v_K$. I find for these parameters $v_h \lesssim 10$ km s^{-1}. For neutron star, with $v_j \simeq 10^5$ km s^{-1}, $\zeta \sim 10^{-8}$and $\theta \simeq 0.1$, similar values are obtained. By equation (11) a swollen WD can have a much higher mass loss rate, but the jet speed will be lower, and the jets will be much less collimated. Over all, the jet's head will proceed at a subsonic speed inside the envelope with $v_h \lesssim 30$ km s^{-1}.

I now examine the distance the jets propagate inside the envelope before slowing down. The total width of the jet at a distance z from the equatorial plane is $2\theta z$. The orbiting jet-blowing companion crosses this distance along its orbital motion in a time of $t_c = 2\theta z / v_K$. During that time the jets proceeds a distance of

$$\Delta z \simeq t_c v_h \simeq 4(\zeta\beta)^{1/2}(a^2+z^2)^{1/2}\left(\frac{v_j}{v_K}\right)^{1/2}\frac{M_2}{M_1(a)}. \tag{16}$$

Note that the distance does not depend on the opening angle of the jet. For the parameters used in the previous example, $\Delta z < 0.1z$. This means that the jet's head at a distance $z \sim a$ from the equatorial plane, will move only a distance $\sim 0.1z$ before the supply of fresh jet's material ends (because the companion moves along its orbit). I found above that the jet's head moves at a subsonic speed of $v_h \lesssim 30~\mathrm{km~s^{-1}}$. Hence, after the supply of fresh jet's material ceases, the jet will not propagate much. Even if exit the envelope, its speed will be below the escape velocity from the envelope.

These jets have a different large effect on the envelope. The jets shocked to a very high temperature, and form a hot and low-density bubble, which is then buoyant outward, and ,mechanically disturbed the envelope. It is true that the luminosity of the accreting star deposited more energy, but it is thermal energy which the stellar envelope can transport outward via the convective envelope (small fraction of the radiated energy goes to accelerate the wind of RGB and AGB stars). The large bubble (see below) may have a larger effect on the envelope. Let the energy deposited into the shocked jets be $\sim \chi L_{\rm Edd}$. For a mass loss rate into the two jest of $\dot M_j = 0.05 \dot M_{\rm Edd}$ (as noted earlier, due to the nuclear burning, the mass loss rate can be somewhat higher), and jet speed equal to the Keplerian speed at the accreting companion surface, we find $\chi = 0.025$. This energy forms a bubble, whose change of volume rate is given by energy considerations $\dot V \simeq f_b \chi L_{\rm Edd}/P(r)$, where $P(r)$ is the pressure in the envelope, and $f_b = 0.4$ for an adiabatic index of $\gamma = 5/3$. For a $\sim 1 M_\odot$ envelope a good approximation is (Soker & Harpaz 1999)

$$P(r) \simeq 10^5 \left(\frac{r}{100 R_\odot}\right)^{-3}~\mathrm{erg~cm^{-3}}. \tag{17}$$

During one orbit, of duration $\tau_K \simeq 0.3(r/100R_\odot)^{3/2}$ yr, the ratio of the volume filled by the shocked two-jets' material V_K, to the volume inner to the orbit is, for $L_{\rm Edd} = 10^{38}~\mathrm{erg~s^{-1}}$,

$$\frac{V_K}{4\pi r^3/3} \simeq 0.05 \left(\frac{r}{100R_\odot}\right)^{3/2}\left(\frac{\chi}{0.025}\right). \tag{18}$$

However, the orbit-decay time is longer than τ_K (Hjellming & Taam 1991). Substituting 1 yr instead of τ_K, gives

$$\frac{V(1~\mathrm{yr})}{4\pi r^3/3} \simeq 0.2\left(\frac{\chi}{0.025}\right). \tag{19}$$

I find that the hot bubble formed by the two jets near orbit of an accreting WD will cause a large disturbance in the envelope. This may facilitate the ejection of the envelope in a CE evolution.

7. THE OVERALL PICTURE

7.1. Momentarily Effects

To put the mechanical energy of jets into the overall picture, I consider 3 mechanisms as orbits shrinks. The first is energy deposition. From the energy (gravitational plus kinetic) of the orbiting binary system, $E_{\rm orb}$, I find (I define positively deposited energy)

$$\frac{dE_{\rm orb}}{da} = \frac{GM_1M_2}{2a^2}. \tag{20}$$

A fraction $1-\alpha_e$ of this energy be radiated away, as the nuclear energy produced by the giant is, and will not be used in expelling the envelope. For an envelope density profile of $\rho \propto r^{-k}$, with $k \simeq 2$, the envelope binding (negative of gravitational) energy is

$$\Delta E_{\rm bind} = B_e \frac{GM_{\rm env}M_1}{R_*}, \tag{21}$$

where $B_{\rm env} \sim 5-10$. The relative energy deposition as the companion spirals-in is defined as

$$D_E(M_2, a) \equiv \frac{\alpha_e}{\Delta E_{\rm bind}} \frac{dE_{\rm orb}}{d\ln a} = \frac{\alpha_e}{2B_{\rm env}} \frac{M_2}{M_{\rm env}} \frac{R_*}{a} = 0.05 \frac{\alpha_e}{0.5} \left(\frac{B_{\rm env}}{5}\right)^{-1} \frac{M_2}{M_{\rm env}} \frac{R_*}{a}. \tag{22}$$

This quantity represents the relative importance of the orbital energy deposited into the envelope as the orbit shrinks by a short radial distance $da \ll a$.

The rate of orbital angular momentum deposited to the envelope as the orbit shrinks is given by

$$\frac{dJ_o}{da} = \frac{1}{2} \left[\frac{G(M_1+M_2)}{a}\right]^{1/2} \frac{M_1M_2}{M_1+M_2}. \tag{23}$$

The moment of inertia of the envelope, for the density profile assumed above, is $I_{\rm env} = k_e M_{\rm env} R_*^2$, with $k_e \simeq 0.2$. The maximum angular momentum of the envelope, assuming a uniform rotation is then

$$J_{\rm env}({\rm max}) = k_e M_{\rm env} (GM_1R_*)^{1/2}. \tag{24}$$

The relative importance of angular momentum deposition is defined as

$$D_J \equiv \frac{1}{J_{\rm env}({\rm max})} \frac{dJ_o}{d\ln a} = \frac{1}{2k_e} \frac{M_1^{1/2}}{(M_1+M_2)^{1/2}} \frac{M_2}{M_{\rm env}} \left(\frac{a}{R_*}\right)^{1/2} \simeq 2 \frac{M_2}{M_{\rm env}} \left(\frac{a}{R_*}\right)^{1/2}, \tag{25}$$

where I used $M_1 \gg M_2$ in the last equality. Note that D_J is not identical to the $\gamma_{\rm CE}$ parameter defined as the envelope spinning-up time scale to the orbital decay time scale (Livio & Soker 1988), although they are similar in representing the significance of envelope spin-up. Here D_E and D_J represent the effects of energy and angular momentum deposition, respectively, as the orbit shrinks by a small amount da.

The mechanical energy deposited by the jets (including both the PdV work and the internal energy of the gas inside the bubble) depends on several poorly known parameters, i.e., χ and the time-scale for orbital decay $\tau_d = a/\dot{a}$. Using the Eddington accretion rate from equation (4) with its Eddington luminosity and the jets' mechanical energy used in equations (18) and (19), and using the envelope binding energy used above, the relative importance of the mechanical energy of the jets is defined as

$$D_{\rm acc} \equiv \frac{\tau_d \chi L_{\rm Edd}}{\Delta E_{\rm bind}} = 0.25 \left(\frac{B_{\rm env}}{5}\right)^{-1} \left(\frac{M_1}{M_\odot}\right)^{-1} \frac{R_*}{500 R_\odot} \frac{\tau_d}{100 \text{ yr}} \frac{\chi}{0.025} \frac{M_2}{M_{\rm env}}. \tag{26}$$

The long decay time-scale used here is appropriate when the companion is in the outer regions of the giant's envelope.

In Figure 1 I plot the three functions, D_E, D_J, and $D_{\rm acc}$, with the same scaling as used in equations (22), (25), and (26), respectively. I note the following: (1) The three functions depend in the same way on $M_2/M_{\rm env}$. (2) If $D_J \gtrsim 1-3$ and the giant's radius does not expand to the initial orbital separation, the system will not enter a CE phase; the exact value depends on how much angular momentum is removed by the wind. Hence a CE with giant at late stages requires $M_2 \lesssim M_{\rm env}$. (3) The deposition of angular momentum by itself does not remove the envelope. But rotating giants may be more efficient in utilizing the luminosity to expel the envelope, e.g., by forming more dust. (4) If D_J is larger, the spiraling-in takes more time, because there is a need to remove angular momentum from the system. This increases τ_d, hence $D_{\rm acc}$ becomes larger. (5) In most cases the orbital energy deposited into the envelope becomes significant only when the companion is deep in the envelope. At very small orbital separation the companion may loss mass to the giant's core (e.g., Ivanova, Podsiadlowski & Spruit 2002), releasing more gravitational energy. (6) At early stages, deposition of angular momentum, which may help forming dust, and the mechanical energy released by the accreting companion plays a larger role than the orbital energy is in expelling the envelope (in addition to the 'regular' RGB and AGB wind). This may end with large post-CE orbital separation (Soker & Harpaz 2003).

7.2. Accumulated Effects

A more appropriate indicator for the significant of the different processes is their accumulated effect. I repeat here the treatment of the previous subsection, but with the total deposited energy and angular momentum. The total energy deposited by the companion as it spirals-in from initial orbital separation a_0 to a is

$$\Delta E_{\rm orb} = \frac{G M_1 M_2}{2a} \left(1 - \frac{a}{a_0}\right). \tag{27}$$

Again, a fraction $1 - \alpha_e$ of this energy be radiated away. The total relative energy deposition as the companion spirals-in, the energy factor, is defined as

$$A_E(M_2, a) \equiv \frac{\alpha_e \Delta E_{\rm orb}}{\Delta E_{\rm bind}} = \frac{\alpha_e}{2 B_{\rm env}} \frac{M_2}{M_{\rm env}} \frac{R_*}{a} \left(1 - \frac{a}{a_0}\right). \tag{28}$$

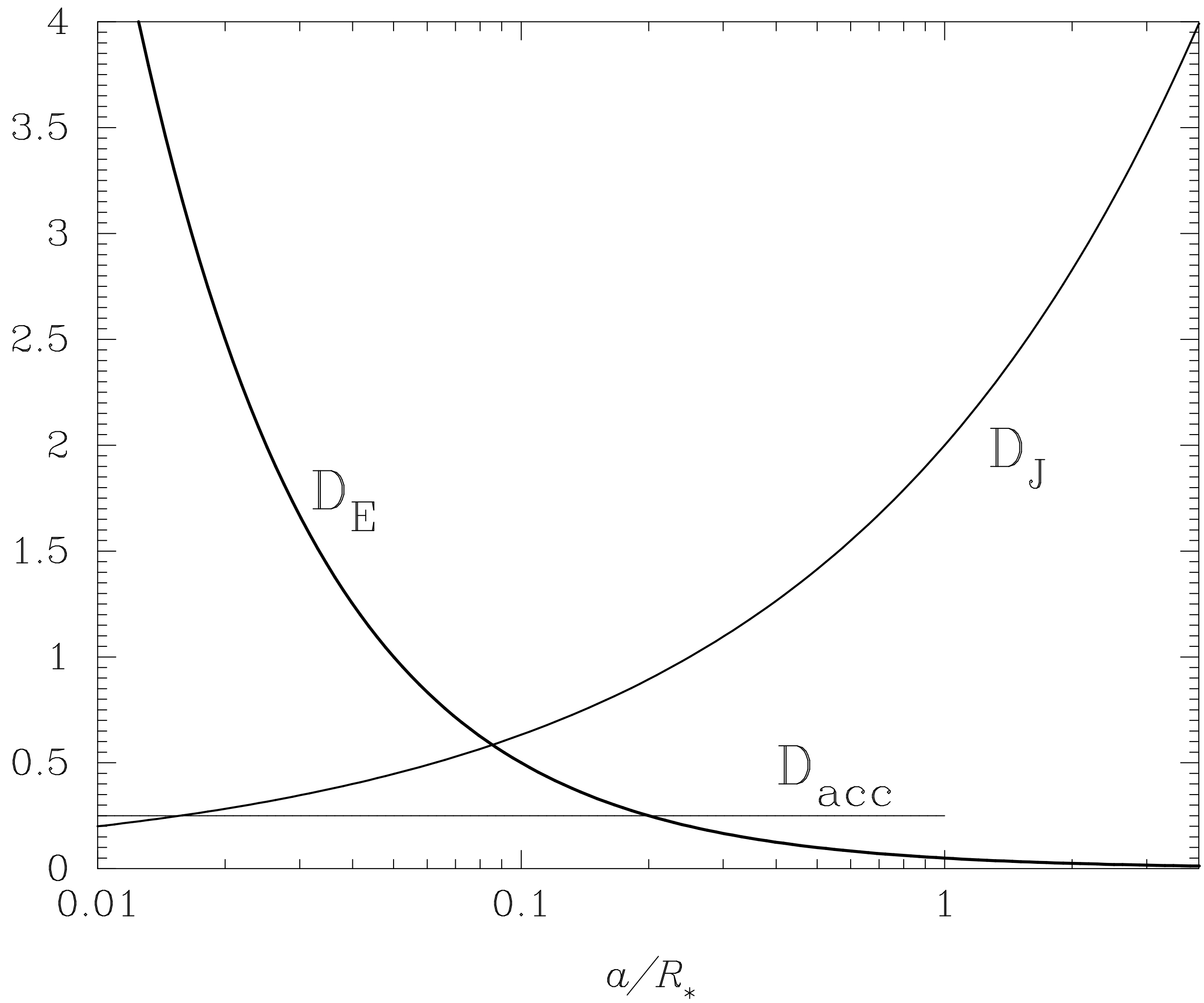

Fig. 1.— The relative importance of the deposition of three quantities to the common envelope as the orbit shrinks by a small amount $da \ll a$, as a function of the orbital separation a, in units of the giant's radius R_*. Drawn are the deposited orbital energy relative to the envelope binding energy $D_{\rm E}$ (eq. 22), the deposited orbital angular momentum relative to the maximum possible for the giant's envelope D_J (eq. 25), and the mechanical energy of the companion's jets relative to the envelope binding energy $D_{\rm acc}$ (eq. 26).

The orbital angular momentum deposited to the envelope as the orbit shrinks is given, for $M_1 \gg M_2$, by

$$\Delta J_o = (G M_1 a_0)^{1/2} M_2 \left[1 - \left(\frac{a}{a_0} \right)^{1/2} \right]. \tag{29}$$

I assume that angular momentum deposition starts with tidal interaction, when $a_0 \sim 4R_*$, and use this value for a_0. The total angular momentum depostion factor is defined by

$$A_J \equiv \frac{\Delta J_o}{J_{\rm env}({\rm max})} = \frac{1}{k_e} \frac{M_2}{M_{\rm env}} \left[1 - \left(\frac{a}{a_0} \right)^{1/2} \right]. \tag{30}$$

The ratio of the angular momentum factor to the energy factor is

$$\frac{A_J}{A_E} = 100 \left(\frac{k_e}{0.2} \right)^{-1} \left(\frac{\alpha_e}{0.5} \right)^{-1} \left(\frac{B_{\rm env}}{5} \right) \frac{a}{R_*} \left[1 + \left(\frac{a}{a_0} \right)^{1/2} \right]^{-1}. \tag{31}$$

For the parameters used to scale the last equation, it turns out that energy deposition dominates over angular momentum deposition only when $a \lesssim 0.01 R_*$. For a giant of $R_* \sim 1$ AU, this occurs when $a \sim 2 R_\odot$. By then many companions will go through a RLOF process. My conclusion is that for the mass loss process, in most cases it is angular momentum deposition which causes large effects. This is true mainly in giants which have high mass loss rate, such that the rotating envelope will facilitate much higher mass loss rate, e.g., by enhancing dust formation.

8. SUMMARY

The main goal of the present paper is to point to the caution one must take in using the $\alpha_{\rm CE}$ parameter when studying CE evolution. Namely, the orbital energy deposited to the giant's envelope is not always the main effect leading, directly or indirectly, to the removal of the envelope. For that I considered here the deposition of energy from the accreting companion and the deposition of orbital angular momentum to the giant's envelope. The main results can be summarized as follows.

1. When inside the envelope of a giant, a main sequence companion is unlikely to blow jets, or a collimated fast wind (CFW, i.e., less collimated jets), or it will marginally do so only when in the outer parts of the envelope.

2. A WD companion is more likely to blow jets or a CFW

3. These jets, even if exist, whether from a WD or a MS companion, are not likely to exit the envelope at a high speed during the CE phase. Hence, they are not likely to play a major role in shaping the circumbinary matter. Jets might be blown by the companion before entering the CE (Soker & Rappaport 2000), or one or two of the stars after the CE ends (Soker &

Livio 1994). This explains the observations that PNs with binary nuclei are not bipolar PNs, i.e., have no lobes, beside NGC 2346, with the longest known orbital period. I do expect that some binary progenitors of bipolar PNs entered the CE phase at late stages, and that now the orbital separation is $\sim 0.1 - 1$ AU. These systems are hard to detect (Bond 2000). To obtain a quantitative result, the CE population synthesis calculations of Yungelson, Tutukov, & Livio (1993) should be repeated but with enhanced mass loss rate from rotating AGB stars included.

4. The CFW or jets, if exist, may inflate a bubble (with a complicated structure because of the orbital motion), hence playing a significant role in expelling the outer layers of the envelope when the companion is still orbiting in the outer envelope region.

5. In many cases the effects due to angular momentum deposition into the envelope seem more influential in removing the envelope than orbital energy deposition, assuming that fast rotating envelopes have high mass loss rates. This is true for stellar as well as substellar companions. The energy source is the giant luminosity due to nuclear energy production in the core. The Eddington luminosity of an accreting stellar companion is of the order of the giant's luminosity, and can farther increase the mass loss rate (Iben & Livio 1993; Armitage & Livio 2000).

6. My results here iterate earlier claims (Soker 2002; Soker & Harapz 2003) that a high degree of cautious should be taken when applying the $\alpha_{\rm CE}$ parameter for the removal of CEs. For example, the conclusions of some papers that another energy source, e.g., ionization energy of the envelope, is required to remove the envelope (see criticism in Soker & Harpaz 2003) are questionable.

I thank Mario Livio for very helpful and detailed comments at the beginning of this project. This research was partially supported by the Israel Science Foundation.

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